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Concept of operations for channel characterization and simulation of coaxial transmission channels at the National Ignition Facility (NIF)

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Concept of operations for channel characterization and simulation of coaxial transmission channels at the National Ignition Facility (NIF)

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Abstract

The National Ignition Facility (NIF) at Lawrence Livermore National Laboratory (LLNL) executes experiments for inertial confinement fusion (ICF), world-class high energy density physics (HEDP), and critical national security missions. While the laser systems, target positioners, alignment systems, control systems, *etc.* enable the execution of such experiments, NIF's utility would be greatly reduced without its suite of diagnostics. It would be effectively "blind" to the incredible physics unleashed in its target chamber. Since NIF diagnostics are such an important part of its mission, the quality and reliability of the diagnostics, and of the data recorded from them, is crucial.

It is well known that the coaxial transmission channel between a diagnostic and its recording system distorts the data, as thus the physics, observed by the diagnostic's sensor. Methods are available for partially compensating for the distortion, but they rely on accurate *channel characterization.* Further, in order to understand the impact of the distortions on signals of interest, a *channel simulation* capability is needed. Channel simulation is useful for diagnostic design and diagnostic design reviews, particularly in the conceptual stage, through meaningful specifications and virtual testing during design.

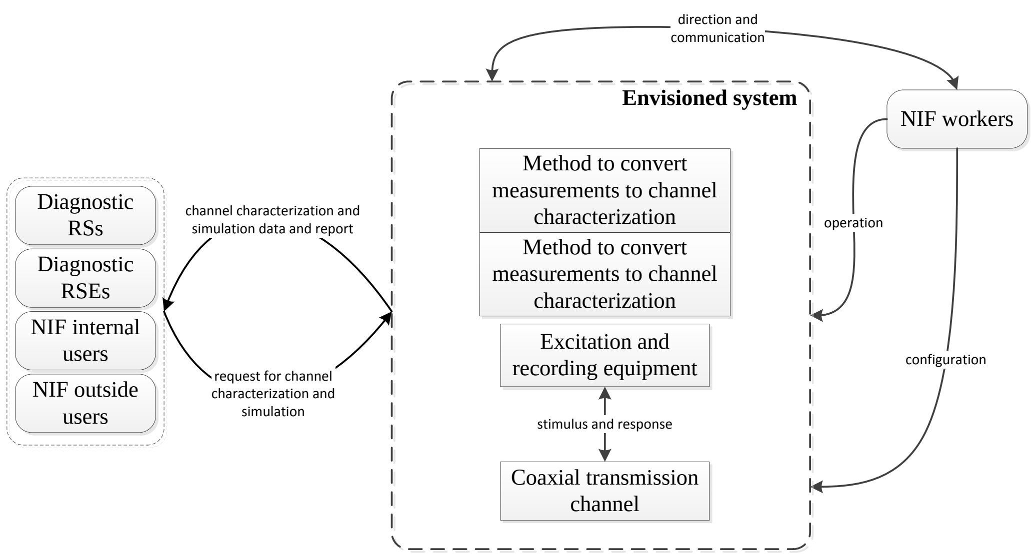
The subject of this proposal report is a system for coaxial transmission channel characterization and simulation that could increase the reliability of and confidence in some experiments at NIF, generally for those currently outside of the official NIF data processing system. Such experiments include those of outside users and some internal NIF users, particularly with new and/or temporary coaxial transmission channels that are a part of experiments that occur infrequently. This encompasses a large portion of national security experiments and some internal NIF proof-of-concept and prototyping tests.

Key stakeholders in this proposed channel characterization and simulation system include the NIF User Office, Target Diagnostics management, NIF management, outside and internal NIF users, NIF workers, and Diagnostic Responsible Scientists and Systems Engineers.

Some of the constraints that the project will respect are minimal funding and NIF policies and procedures, including safety and not impacting the shot schedule. In addition to these and other constraints, the key stakeholders have this set of ultimate expectations for the project:

1. Accurate
2. Reliable
3. Available to users for their own independent use
4. Simple to implement
5. Simple to use
6. Reasonably fast
7. Ability to provide accuracy information

In order to satisfy the constraints and meet or exceed the expectations, I propose a transmission channel characterization and simulation system consisting primarily of a pulse generator and oscilloscope and computer codes. The computer codes would convert the oscilloscope measurements into an impulse response (channel characterization) and estimate the output for arbitrary inputs using the impulse response (channel simulation). I arrived at this particular recommendation through a system engineering study of the stakeholders' expectations and the pros and cons of a number of potential concepts. See the figure below for a high-level depiction of the proposed system, along with interactions with the key active stakeholders:



The report provides more detail on the interactions among the key active stakeholders and the internal elements of the system.

One substantial addition to the NIF diagnostic community is the introduction and use of a trusted simulation method to complement channel characterization. Another, perhaps less substantial, is the intent to distribute the proposed system more widely among users that currently are not a part of the official NIF data processing system.

Contents

1 Mission Description

1.1 Introduction

The National Ignition Facility (NIF) at Lawrence Livermore National Laboratory (LLNL) is the highest energy laser in the world [1]. With its 192 beams focused on pencil-eraser-sized targets in a 10 m diameter target chamber, it executes experiments for inertial confinement fusion (ICF), world-class high energy density physics (HEDP), and critical national security missions. While the laser systems, target positioners, alignment systems, control systems, *etc.* enable the execution of such experiments, NIF's utility would be greatly reduced without its suite of diagnostics. It would be effectively "blind" to the incredible physics unleashed in its target chamber. Figure 1 depicts the role that diagnostics play in observing experiments in the target chamber. NIF diagnostics observe a wide range of phenomena, such as x rays, neutrons, electromagnetic fields, shock waves, *etc.* Signals from their observations travel along a *transmission channel*, which varies according to the diagnostic, but can include coaxial cables, fiber optics, twisted pair, and a host of connectors, adapters, filters, and attenuators. All of this intervening hardware impacts the quality of the signals, corrupting them to some extent. The transmission channel can be very long, sometimes greater than 100 ft., which can greatly increase the distortion of the signals. Toward the end of the transmission channel is a variety of recording devices, including oscilloscopes, data loggers, digitizers, *etc.* These devices receive the signals from the transmission channel and record them as *data*, which is the "deliverable" for the whole system, as indicated in Fig. 1. The recording devices further distort the signals. The distortion introduced by the transmission channel causes the recorded data to be different from what the diagnostics initially observed (Fig. 2).

Fortunately, most of the distortions can be reduced by a process called *channel equalization*. Channel equalization is essentially correcting for the deleterious effects of the transmission channel on the data. In order for channel equalization to be effective, the distortion characteristics of the transmission channel must be known. The process of determining the distortion characteristics of the transmission channel is called *channel characterization*. Both channel characterization and equalization are necessary to reduce the effects of the transmission channel on the data. Related to channel characterization and equalization, and relying on channel characterization, is transmission *channel simulation*, which provides the capability to predict the transmission channel's output given arbitrary inputs. Refer to Fig. 3 for relationships among channel characterization, simulation, and equalization.

Channel simulation is extremely useful for diagnostic design, as it allows the designer to estimate the output of the transmission channel for realistic signals of interest. Such information could be applied to select adequate components and, perhaps even more importantly, to facilitate realistic expectations of the transmission channel, when it comes time to interpret actual data.

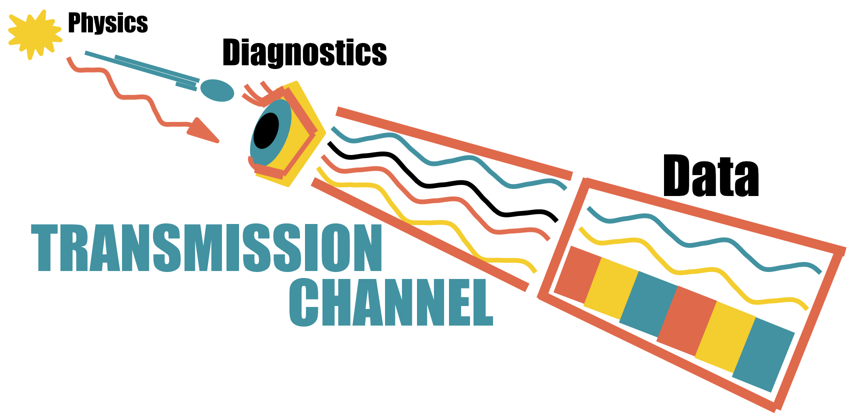


Figure 1: NIF diagnostics observe a wide range of *physics*. Signals from their observations travel along a *transmission channel*, *e.g.*, coaxial cables, fiber optics, twisted pair, *etc.*, with recording devices toward the end of the transmission channel. The distortion introduced by the transmission channel causes the recorded *data* to be different from what the diagnostics initially observed.

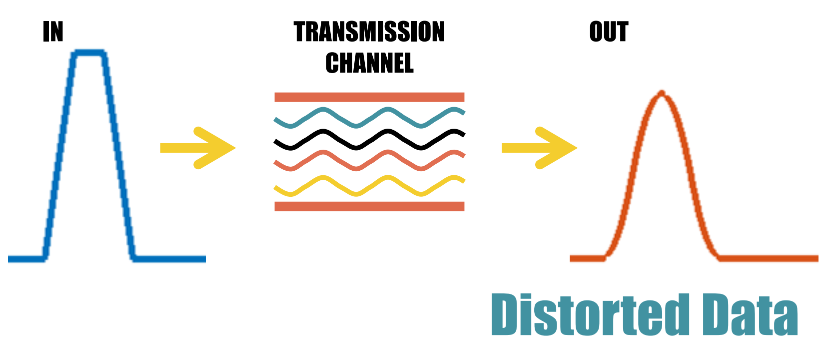


Figure 2: The transmission channel distorts the signals to some extent, yielding recorded data that is different from what the diagnostics initially observed.

In this document, I will address only channel characterization and simulation of coaxial-cable-based transmission channels (here referred to as *coaxial transmission channels*) from the output of the sensor (the *input signal*) to the output of the channel, excluding the recording device, denoted the *output signal*. See Fig. 3. Channel equalization is beyond the scope of this document. I have planned a follow-on study to include channel equalization.

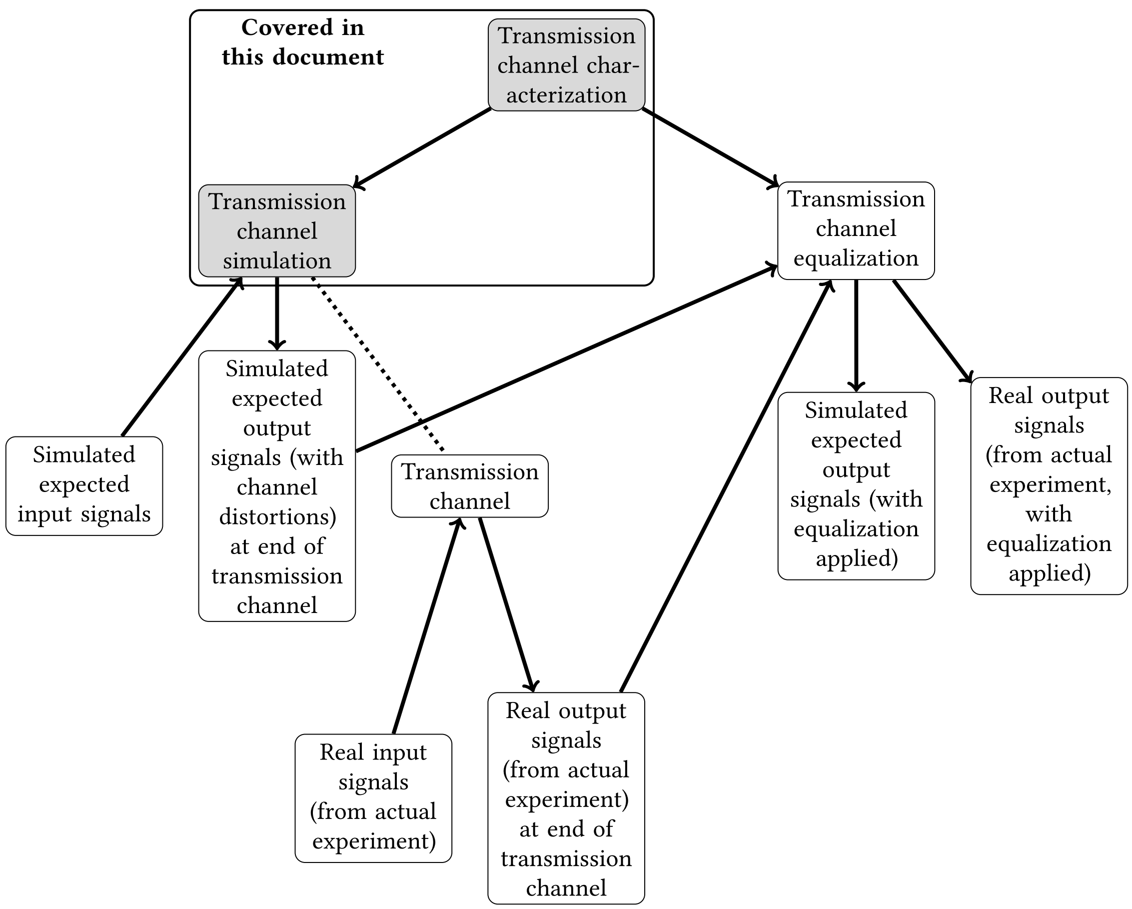


Figure 3: Relationships among transmission channel characterization, simulation, and equalization. This document addresses only transmission channel characterization and simulation, which are highlighted in the figure. A follow-on study is planned for transmission channel equalization.

1.2 Need

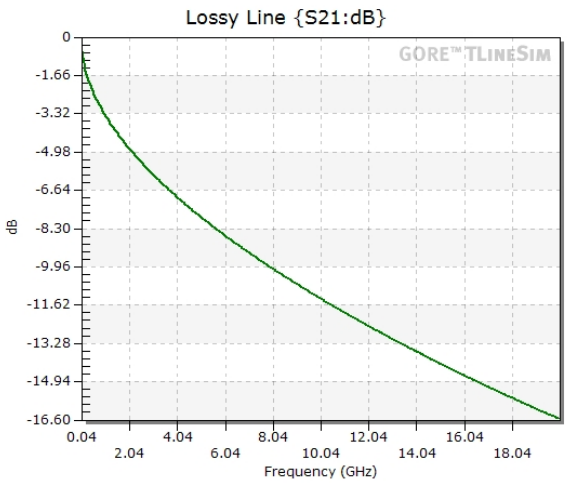
NIF has a solid capability for channel characterization. However, that capability is structured for long-term, high-priority diagnostics. Since outside users, and even some internal NIF users, fielding new diagnostics based on coaxial transmission channels are often outside of that system, at least initially, there is a need to provide them with comparable channel characterization and simulation capabilities until they can be assimilated into the standard NIF system. This is particularly an issue with new and/or temporary transmission channels that are a part of experiments that occur infrequently, which includes a large portion of national security experiments and some internal NIF proof-of-concept and prototyping tests. Even the permanent NIF coaxial transmission channels, which have been characterized, could use improved characterization and simulation for the aforementioned stakeholders. Even though NIF has the capability for channel characterization, there is currently no standard transmission channel *simulation* capability tied into channel characterization for NIF. Currently that capability is scattered among the various users, both internal and external. Here are a few concrete examples that illustrate the state of channel characterization and simulation at NIF:

- One outside user team fielded an instrumented experiment inside the NIF Target Chamber (TC), using a portion of the NIF coaxial transmissions channels, to which they added their temporary coaxial transmission channels. They made a special trip to NIF to perform their own channel characterization using their own trusted method [2] on surrogate test hardware. **NIF needs to develop its own trusted method of channel characterization and simulation that outside users can employ if they so choose. Such a method should include *in situ* capability, if possible, instead of just lab measurements on surrogate test hardware.**
- Another outside user team will be fielding an instrumented experiment inside the NIF TC. They will use the *entire* length of the NIF coaxial transmissions channels, from the TC to the Diagnostic Mezzanine (DM), for a total length of over 150 ft. of coaxial cable! They will definitely need channel characterization and simulation for experiment design, and NIF could work with them to provide that. **NIF needs to develop a method of channel characterization and simulation for outside users that might not have their own capability.**
- After an acceptance test on a NIF cable channel, a manager looked at the pertinent network analyzer [3] insertion loss data (essentially a plot of what effect the cable has on sine waves over a wide range of frequencies—a *frequency-domain* [4] plot) and made this very wise observation:

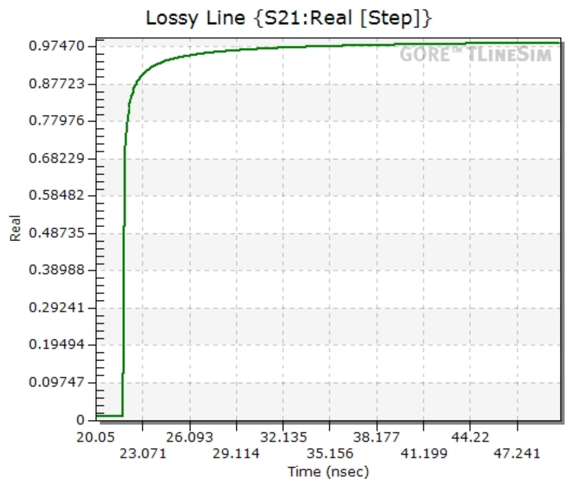
> *The results here do not talk about any specs. You talk about the sources of issues and the levels but do you indicate if these wiggles and bumps are as expected and [acceptable] or we need to do better[?] Can you qualify if this is good enough or needs attention[?]* [5]

Essentially, the plot might have looked something like Fig. 4a. It is possible to put specifications on such a measurement, but it is much more meaningful to have a plot like Fig. 4b, which is the step response (a *time-domain* [6] plot) of the cable from Fig. 4a. Here we can talk about specifications on rise time, overshoot, ringing, *etc.*, that might be much more meaningful to NIF and are certainly easier to explain. **NIF needs to develop a method of channel characterization and simulation for internal users to evaluate acceptance test measurements against meaningful specifications.**

- An effort to introduce remote attenuators into NIF is underway (*c.f.*, [7]). One of the key issues of this effort is how the new attenuator systems will affect the signals that pass through them. A related issue is whether the signal distortions will be within some meaningful specifications. **An accepted channel characterization and simulation method would facilitate evaluation of acceptance test measurements against meaningful specifications.**
- A new diagnostic is under development for deployment at NIF. It will need to have a coaxial transmission channel of about 150 ft. of LMR-600 (a low-loss coaxial cable). During a review, one of the reviewers asserted that the cable would not meet the specifications. He based his argument on the frequency-domain concept of *bandwidth*, which works well for sine wave signals but can be problematic for specifications that are more naturally cast in time-domain terms. **An accepted channel characterization and simulation method would assist diagnostic design and design reviews through meaningful specifications and virtual testing capability during the design phase.**



(a) Insertion loss S_{21}



(b) Step response

Figure 4: Simulation of insertion loss S_{21} and step response for a lossy cable using the on-line simulator at Ref. [8]

In summary, a distilled version of the conclusions of need from the examples above is

The Need

NIF needs to develop a trusted method of channel characterization and simulation that both internal and outside users, those not yet included in the standard NIF system, can employ if they so choose. Such a method would ideally facilitate evaluation of acceptance test measurements against meaningful specifications and assist in diagnostic design and design reviews.

1.3 Stakeholders, Expectations, and Constraints

Stakeholders in a NIF coaxial transmission channel characterization and simulation system include (also refer to Fig. 5)

Outside NIF users NIF users that *are not* listed on the NIF organizational chart.

Internal NIF users NIF users that *are* listed on the NIF organizational chart.

NIF policies and procedures includes safety, security, reviews, work approval methods, *etc.*

Funding NIF funding or funding from outside sources.

NIF-related lab work prototyping or testing NIF diagnostics and transmission channels outside of the NIF facility.

User office provides support for NIF users, particularly outside users.

TD management Target Diagnostics (TD) management includes personnel that have oversight responsibilities for diagnostics in NIF, including diagnostics fielded by outside users.

NIF management includes personnel that manage the NIF programs and facility.

NIF workers Personnel that perform support work in the NIF facility, such as connecting cables, making measurements of transmission channels, transporting and loading diagnostics, *etc.*

Data systems group is responsible for developing and maintaining systems to collect, process, and archive data from NIF diagnostics.

NIF diagnostics includes various sensors that observe a wide range of physical phenomena in NIF. They require transmission channels to pipe those observations out to be recorded and processed.

NSTec Livermore traditionally has characterized transmission channels in NIF.

Diagnostic RSEs *Responsible Systems Engineers* that have engineering responsibilities for certain diagnostics.

Diagnostic RSs *Responsible Scientists* that have scientific responsibilities for certain diagnostics. They are usually physicists.

Fixed NIF coaxial transmission channels include coaxial transmission channels that are more or less a permanent part of the NIF facility. An example is the cable run from the TC, through the DIMs and facility conduit, to the DMs.

Temporary coaxial transmission channels in NIF include coaxial transmission channels that do not remain deployed in the NIF facility, but are installed before and removed after each pertinent experiment campaign. This also includes temporary coaxial transmission channels for other types of temporary experiments.

Note that this list and Fig. 5 include both passive and active stakeholders. *Active stakeholders* "are individuals and organizations that actively interact with the system of interest once it is operational and in use." [9, 2.2.1] *Passive stakeholders* "are other individuals and organizations that influence the success of the deployed system"... but do not "actively interact with the system of interest." [9, 2.2.2] Dividing the stakeholders into passive and active sets yields the following:

- Passive
  - NIF policies and procedures
  - Funding
  - User office
  - TD management
  - NIF management
  - Data systems group
- Active
  - Outside NIF users
  - Internal NIF users
  - NIF-related lab work
  - NIF workers
  - NIF diagnostics
  - NSTec Livermore
  - Diagnostic RSEs
  - Diagnostic RSs
  - Fixed NIF coaxial transmission channels
  - Temporary coaxial transmission channels in NIF

See Fig. 6 for a graphical depiction of the division between the passive and active stakeholders.

I considered all of the stakeholders in Figs. 5 and 6 and listed what I thought their expectations would be, mostly from past experience with the stakeholders. Also, since I fit into a couple of the stakeholder categories, I introduced some of my own expectations. I produced a list of 27 expectations, which I have graphical depicted, along with their relationships to the stakeholders, in Fig. 7. Next, I pared the list of stakeholders down to a list of *key stakeholders*. One of the strategies that I used was to consolidate or group stakeholders: "[b]y clustering stakeholders according to common needs, you'll whittle your list down to a more manageable length, increasing the efficiency and impact of your efforts to meet the right groups' needs." [10]. For instance, I am able to implicitly include *NIF diagnostics*, *Fixed NIF coaxial transmission channels* and *Temporary coaxial transmission channels in NIF* in the various users, workers, and RSEs and RSs based on common needs. The same reasoning works for *NIF-related lab work*. I used another strategy, asking if the stakeholder has a "fundamental" impact on this project [10], to remove the *Data systems group* from the key stakeholder list. This project will be almost entirely independent of the *Data systems group*. Also, the ultimate stakeholder in the *Data system group* would be the *Data systems group leader*, who could be considered grouped under *NIF management*. I can remove *NSTec Livermore* from the key stakeholder list in light of the strategy, "Can you exist without or easily replace the stakeholder?" [10]. NSTec Livermore is critical to NIF work, but this particular project can be accomplished independently. Finally, the *Funding* and *NIF policies and procedures* are better handled as *Constraints* so that the expectations can focus more on technical aspects. Using these strategies, the key stakeholder list becomes

The Key Stakeholders

- Passive
  - User office
  - TD management
  - NIF management
- Active
  - Outside NIF users
  - Internal NIF users
  - NIF workers
  - Diagnostic RSEs
  - Diagnostic RSs

which is much more manageable. See Fig. 8 for a graphical depiction of the key stakeholders and constraints.

The paring down of the stakeholder list to key stakeholders and the assignment of some stakeholders and expectations to constraints allows me to have a shorter list of expectations. Also, I have consolidated *Minimal time to implement* into *Simple to implement*, since they are the same basic idea. See Fig. 9 for a graphical depiction of the final constraints, key stakeholders, and their expectations.

I identify the *sacred* expectations by considering the points of view of the various key stakeholders. From a manager's point of view, the system, in addition to satisfying the constraints, should be accurate, simple, and useful. Outside users, which would be a major driver for the system, would want accuracy, accuracy information, simplicity, and utility. The expectation of simplicity is shared with the NIF workers, too. Thus, some of the sacred expectations should be *Accurate*, *Ability to provide accuracy information*, *Simple to implement*, and *Simple to use*. Outside users are an independent lot, so *Available to users for their own independent use* should be included, too. That leaves two more sacred expectations. I choose *Reasonably fast* and *Reliable*, since the utility will come from satisfying the sacred expectations, and simplicity in description is mostly an issue of presentation. Thus, the list of sacred expectations, roughly in order of importance, and the constraints are

The Sacred Expectations

1. Accurate (characteristic)
2. Reliable (characteristic)
3. Available to users for their own independent use (characteristic)
4. Simple to implement (characteristic)
5. Simple to use (characteristic)
6. Reasonably fast (characteristic)
7. Ability to provide accuracy information (capability)

The Constraints

- Funding
  - Minimal cost for NIF
  - Minimal cost for users
- NIF policies and procedures

  - Clearly-defined scope and system boundaries
  - Procedures well documented
  - Safe for facility
  - Safe for workers
  - Does not negatively impact shot schedule at all
- Does not delay or preclude integration into NIF storage and data processing system
- Does not interfere with operation of NIF data storage and processing system
- Negligible impact on shot operations
- Not delay reporting of results

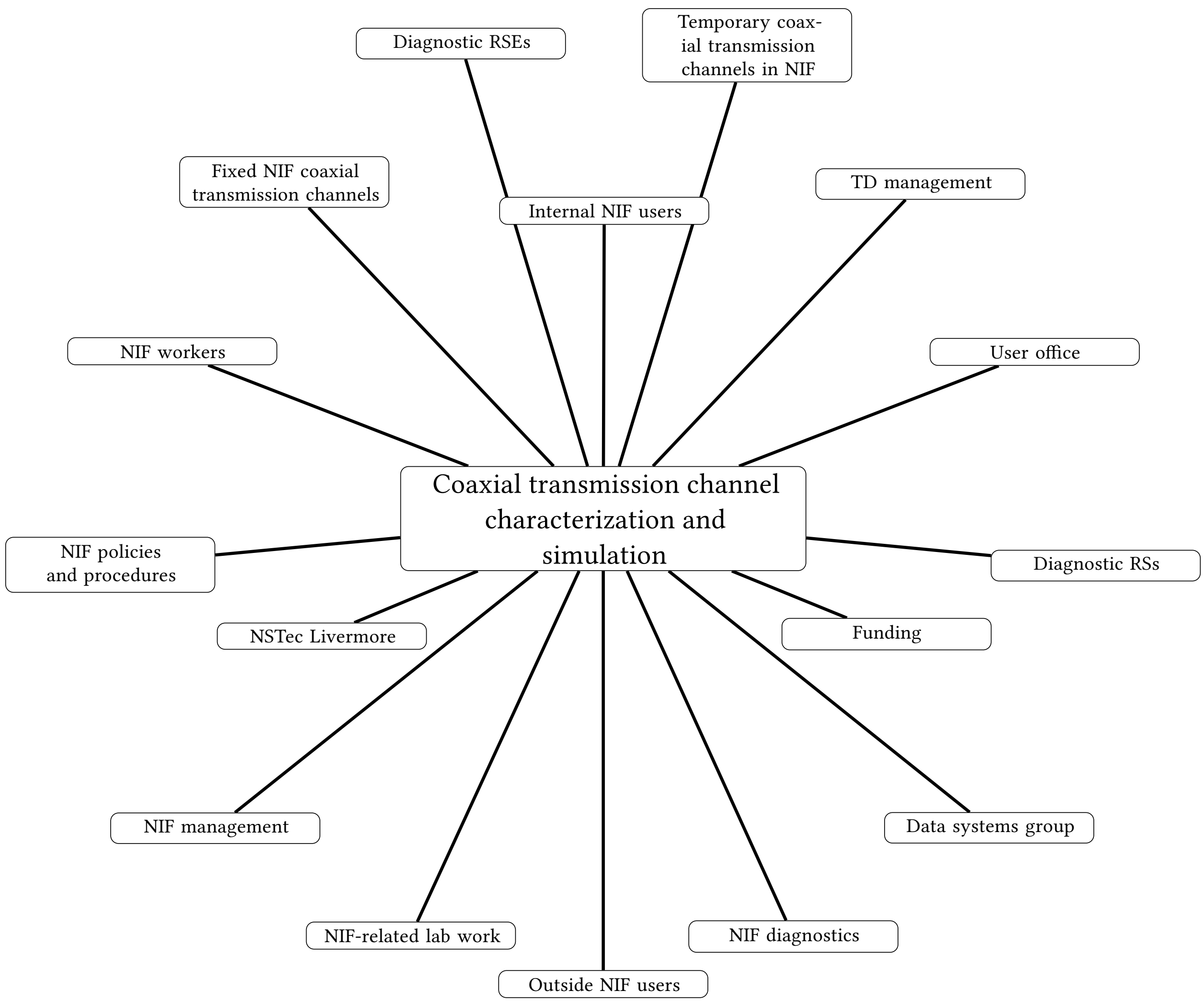


Figure 5: Stakeholder diagram

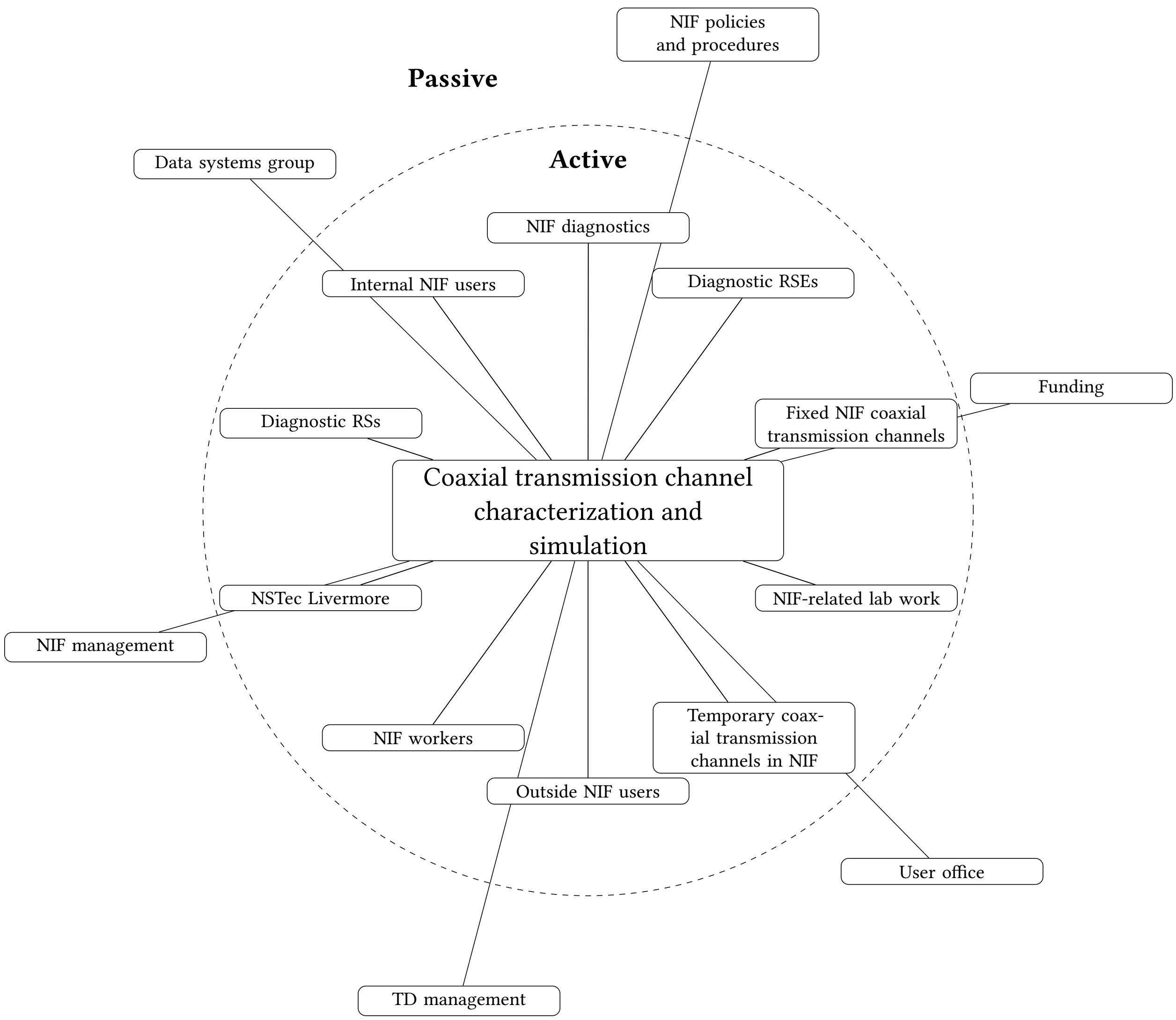


Figure 6: Stakeholder diagram, separated into active and passive stakeholders.

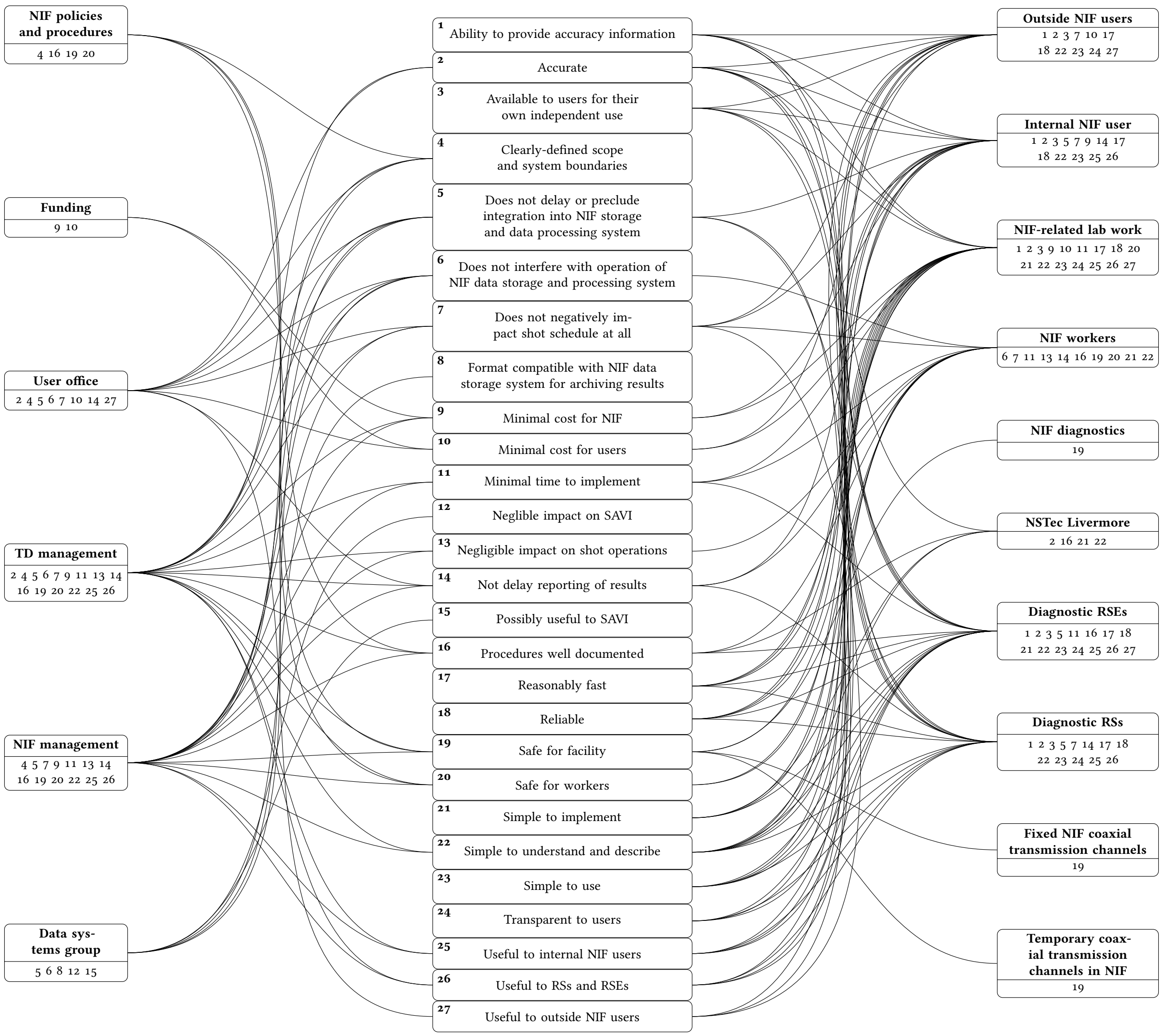


Figure 7: Stakeholder expectations, in alphabetical order. The first column lists the passive stakeholders and the index numbers to their expectations. The third column lists the active stakeholders and the index numbers to their expectations. The second column lists the expectations with index numbers.

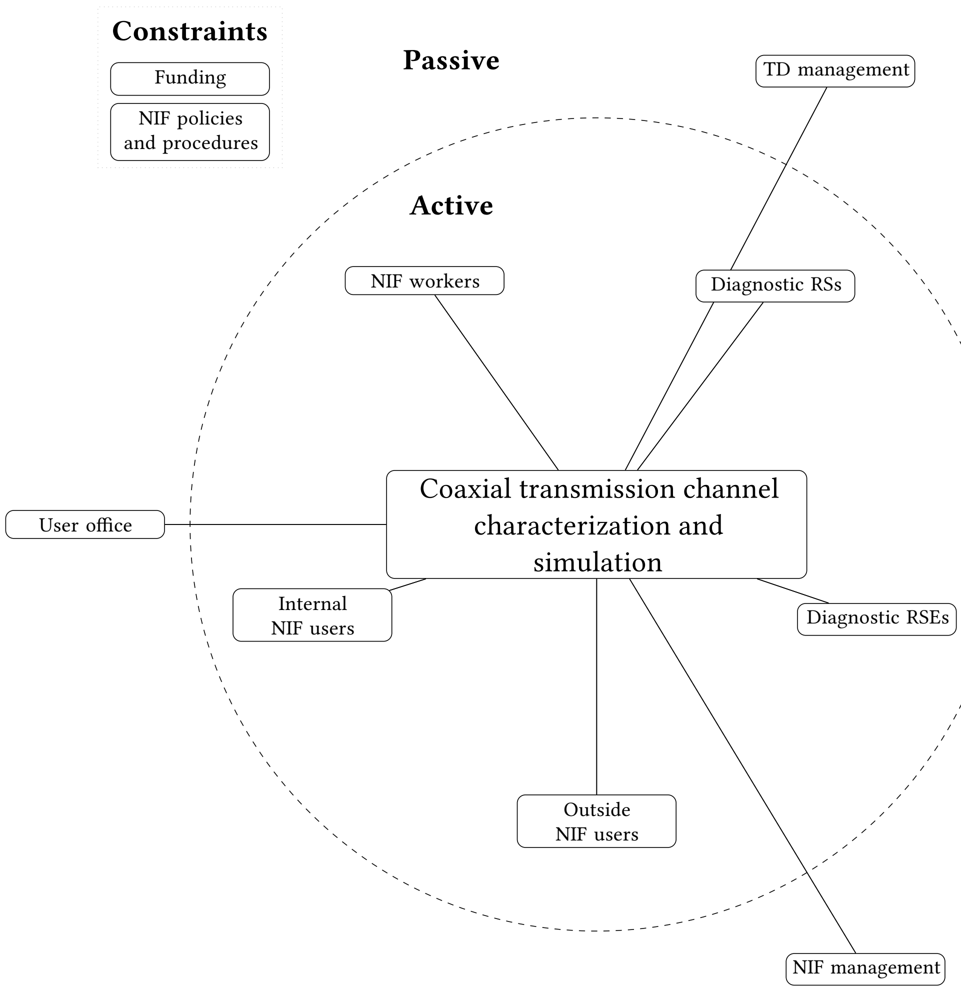


Figure 8: Diagram of key stakeholders, separated into active and passive stakeholders and constraints.

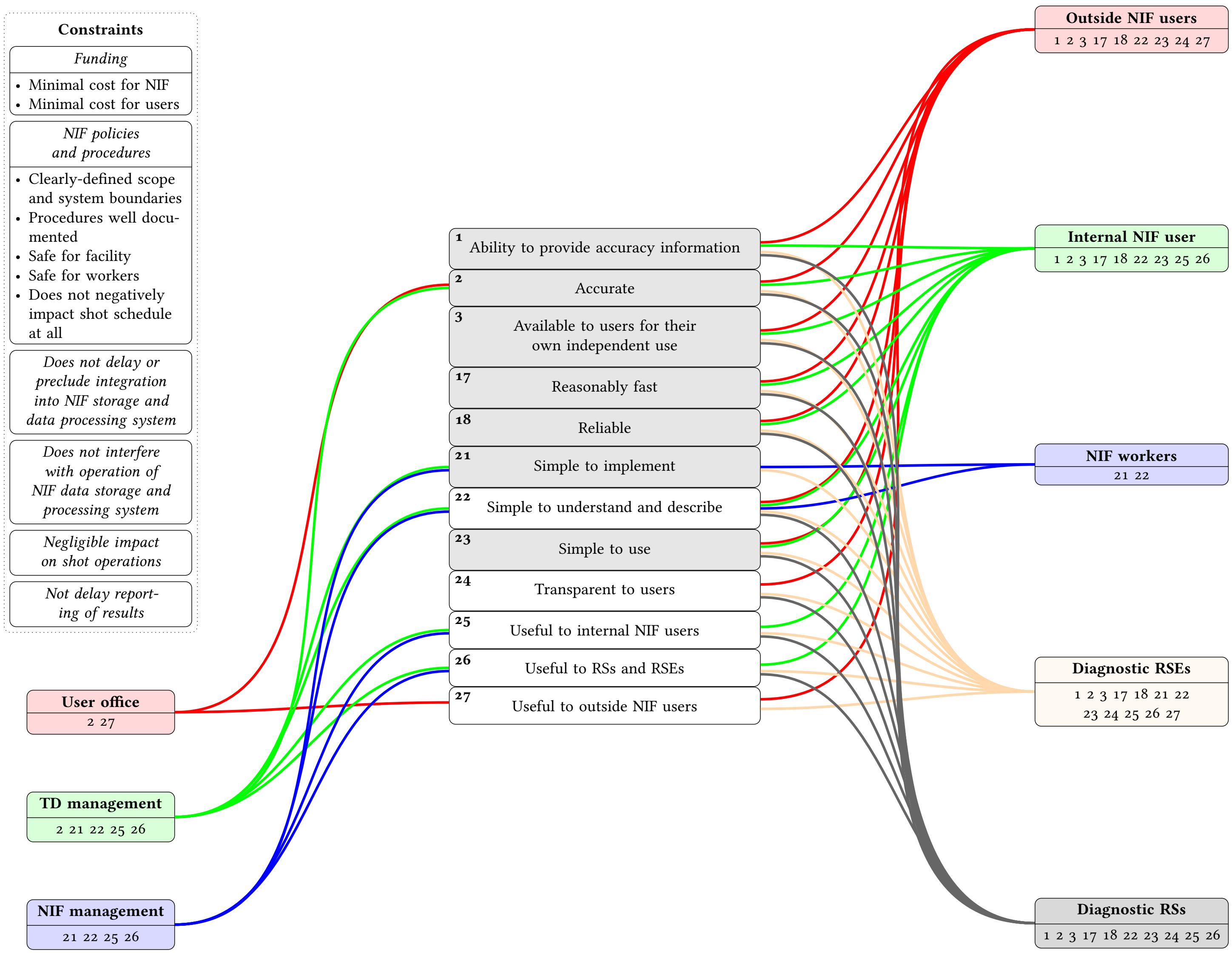


Figure 9: Final expectations of the key active and passive stakeholders and constraints. The sacred expectations (1, 2, 3, 17, 18, 21, and 23) are shaded.

2 System Operational Context and Reference Operational Architecture

The context of the proposed system is best understood by examining in more depth the current state of transmission channel characterization and simulation at NIF, similar to Section 1.2, but somewhat more specific. First, I will examine the most typical route for channel characterization at NIF: time- and frequency-domain characterization by NSTec Livermore. Then I will look at channel characterization by NIF personnel and then conclude with a NIF outside user channel characterization. Since there is currently no standard transmission channel simulation capability tied into channel characterization at NIF (see Sec 1.2), I will not consider channel simulation in the *current* operational context but will in the operational context of the *envisioned* system.

2.1 NSTec channel characterization

The typical channel characterization involving NSTec usually proceeds as follows:

- Diagnostic RS, Diagnostic RSE, or NIF internal user makes request to NSTec for transmission channel characterization.
- NSTec makes measurements, with NIF worker support, in a lab or *in situ* using a
  - step or impulse generator and oscilloscope or
  - vector network analyzer.
- NSTec uses its own in-house process to convert the measurements to frequency response, if necessary.
- NSTec then sends a report with the measurements, frequency response, and discussion of the results.
- NSTec also sends electronic files with the data.
- The diagnostic RS, Diagnostic RSE, or NIF internal user then analyzes the report and data in some sort of way, such as examining the data for signs of unexpected distortion or damage.
- The data can also used in the NIF standard data processing system as calibration information.

2.2 Diagnostic RS, diagnostic RSE, and NIF internal user channel characterization

Another typical scenario involves just the Diagnostic RS, Diagnostic RSE, and NIF internal user, but proceeds in a similar fashion as the NSTec scenario:

- Diagnostic RS or NIF internal user makes request to Diagnostic RSE or NIF internal user for transmission channel characterization.
- Diagnostic RSE or NIF internal user makes measurements, with NIF worker support, in a lab or *in situ* using a
  - step or impulse generator and oscilloscope,
  - time-domain reflectometer, or
  - vector network analyzer.
- Diagnostic RSE or NIF internal user processes the measurements in some fashion to yield, typically, impedance profiles and frequency responses—this is the real transmission channel characterization part of the process.
- The diagnostic RS, Diagnostic RSE, or NIF internal user then analyzes the data in some sort of way, such as examining the data for signs of unexpected distortion or damage. It also is used to guide diagnostic design changes.

2.3 An atypical outside user channel characterization

A final scenario, but not so typical, is the outside user team that followed this procedure:

- NIF outside user made request to Diagnostic RSE and NIF internal user for transmission channel characterization.
- NIF outside user made measurements, with NIF worker, Diagnostic RSE, and NIF internal user support, both in a lab and *in situ* using a step or impulse generator and oscilloscope.
- NIF outside user processed the measurements (the actual channel characterization) to yield calibration data and to check their transmission channel and recording system

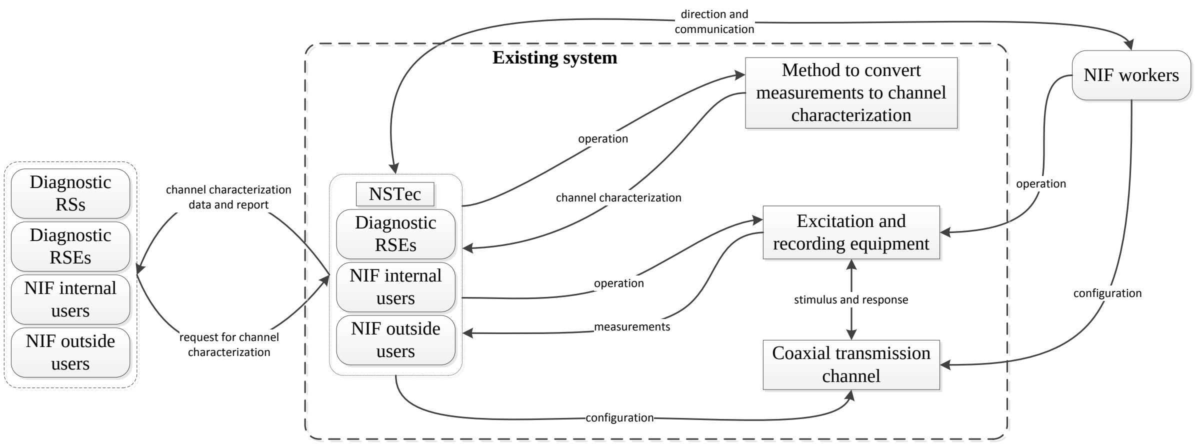


Figure 10: Operational context of existing system

2.4 Operational contexts for existing and envisioned systems

The operational context cases above can be summarized and generalized according to the context diagram in Fig. 10. The operational context of the envisioned system is depicted in Fig. 11. The only major addition to the system is a coaxial transmission channel simulation method to complement and extend coaxial transmission channel characterization. However, I do include the channel characterization method in the scope of this project, too.

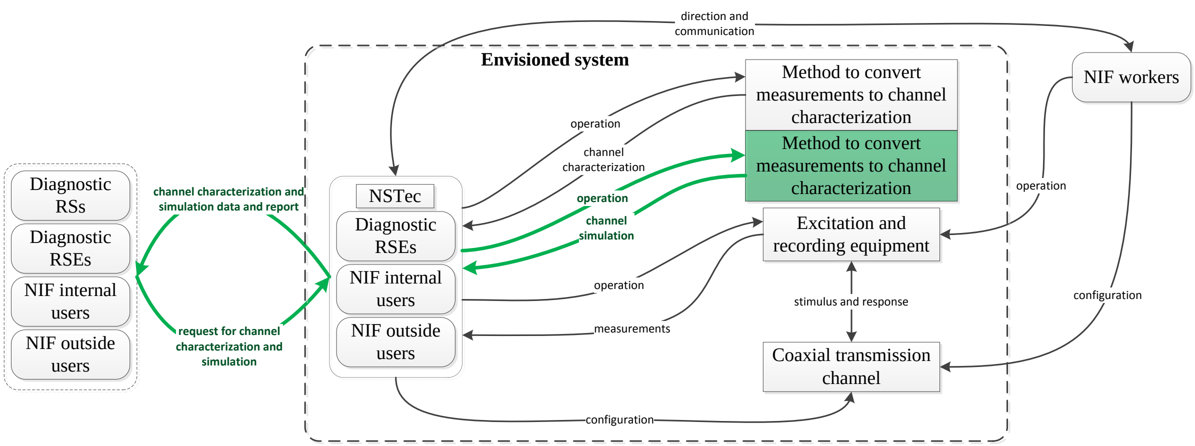


Figure 11: Operational context of envisioned system. The additions to the system are highlighted in green.

3 System Drivers and Constraints

The performance drivers for the envisioned coaxial transmission channel characterization and simulation system are mainly the sacred expectations and the requirements that will be derived from them (Section 7). Refer to Section 1.3 for the derivation of the constraints and a discussion of the constraints in the context of the stakeholders and expectations. See also Figs. 8 and 9. I have repeated the list of the constraints from Section 1.3 below for convenience:

The Constraints

- Funding
  - Minimal cost for NIF
  - Minimal cost for users
- NIF policies and procedures
  - Clearly-defined scope and system boundaries
  - Procedures well documented
  - Safe for facility

  - Safe for workers
  - Does not negatively impact shot schedule at all

- Does not delay or preclude integration into NIF storage and data processing system
- Does not interfere with operation of NIF data storage and processing system
- Negligible impact on shot operations
- Not delay reporting of results

4 Operational Scenarios

A generalization of operational scenarios for the envisioned system has already been described in Section 2 and depicted in Fig. 11. Almost all use cases of the envisioned system can be represented by that general operational scenario. Fig. 12 is a sequence diagram of the context diagram in Fig. 11.

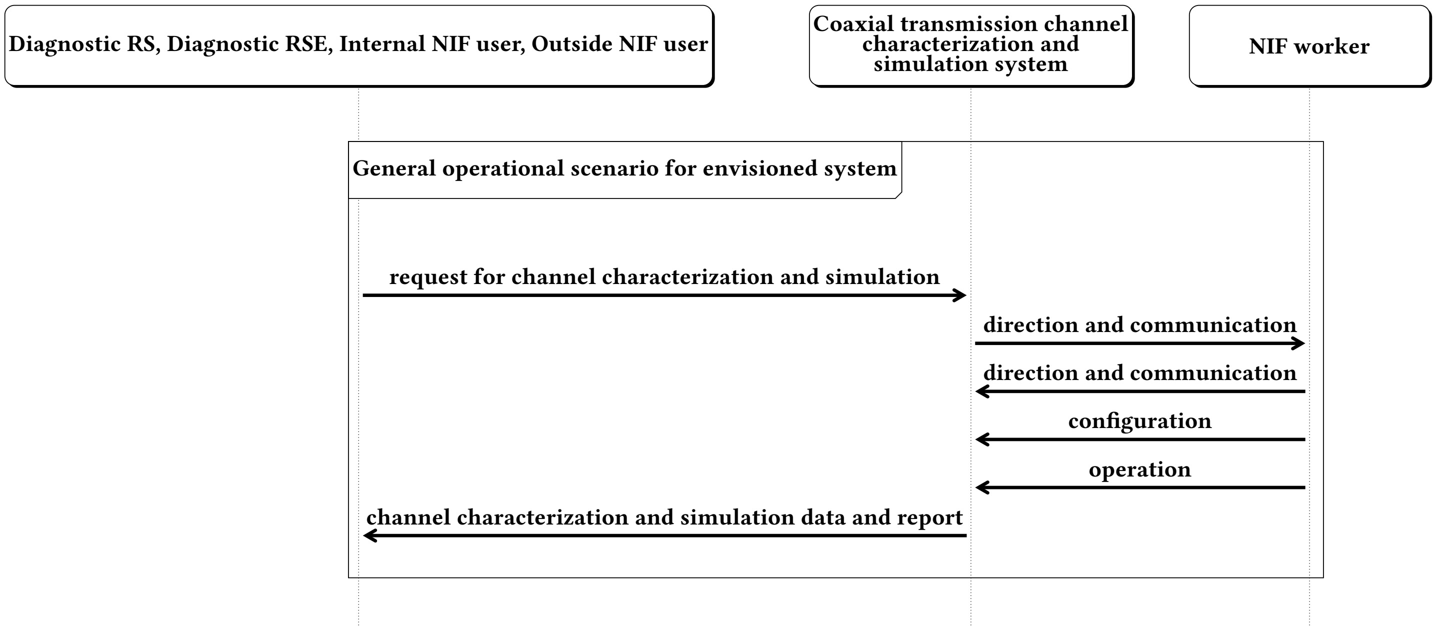


Figure 12: Sequence diagram for general operational scenario for envisioned system. Refer also to Fig. 11.

5 Implementation Concepts Selected and Rationale

Many different implementation concepts are available for the envisioned coaxial transmission channel characterization and simulation system. In order to approach the enumeration of the various concepts and the rationale behind the selection of the favored concepts, I examine two subsystems (refer to Fig. 11):

Subsys. 1— Trusted characterization methods

Subsys. 2— Trusted simulation methods

Other subsystems exist: personnel in the system (*NSTec, RSEs, etc.*), *Coaxial transmission channel*, and *Excitation and recording equipment*. However, none of them, except for perhaps *Excitation and recording equipment*, will change under the envisioned system. I will assume *Excitation and recording equipment* is practically absorbed into Subsys. 1 and 2.

First, I will assemble a list of candidate concepts and then order the concepts against the sacred expectations and constraints using a Pugh matrix [11]. The selected concept for the envisioned system will be the highest-ranked concept from the Pugh matrix.

5.1 Candidate Concepts

In the following sections, I list several different concepts for the envisioned system. They do not form an exhaustive set, but represent salient concepts for the system.

5.1.1 Arbitrary waveform generator and oscilloscope

Perhaps the most straightforward method is to employ an arbitrary waveform generator (AWG) and an oscilloscope. The basic setup is pictured in Fig. 13. The AWG can output signals with arbitrary shape, so approximating an actual signal of interest is possible. If this is the case then the characterization and simulation can be taken care of in the same measurement.

5.1.2 Pulse generator and oscilloscope

A simple alteration of the method in Sec. 5.1.1 is to use an pulse generator and an oscilloscope, instead of an AWG. The setup is pictured in Fig. 14. An pulse generator typically outputs a fixed-shape pulse with only adjustable amplitude. In contrast to the case with the AWG, this method cannot accomplish characterization and simulation in the same measurement, unless the pulse is close enough to the particular signals of interest. For the pulse generator input, some extra post-processing must take place.

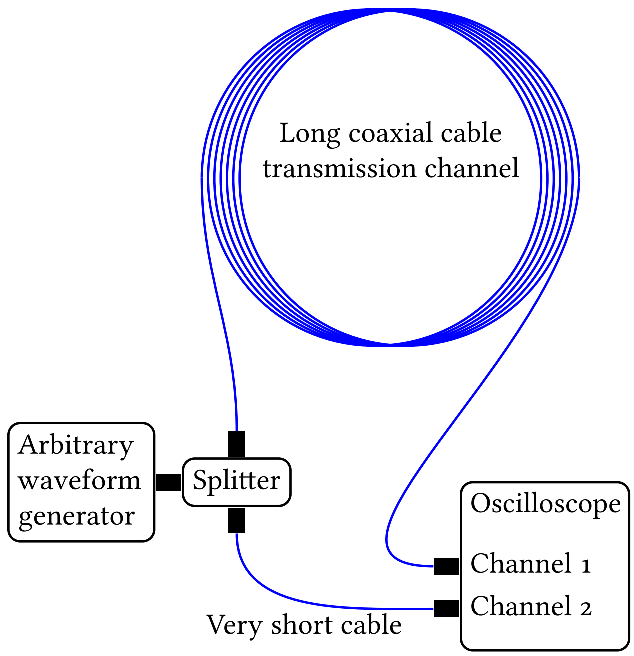


Figure 13: Method using arbitrary waveform generator and oscilloscope.

One way of accomplishing the simulation part is to express the signal of interest, the input signal to the simulation, as a combination of shifted and scaled versions of the pulse generator's output (as recorded on Channel 2 in Fig. 14). Then, the simulated output of the channel is the combination of the channel's response to the pulse generator's output (as recorded on Channel 1 in Fig. 14), using the same shifts and scaling factors as were used on the pulse generator's output. I will denote this concept *pulse generator and oscilloscope—signal combination.*

Another way of simulating the response of the channel to an input signal of interest is to use *system identification* [12] techniques using Channel 2 as the input and Channel 1 as the output. System identification methods will compute an approximate model of the true impulse response of the transmission channel. Once that impulse response model is computed, it can be used to determine the transmission channel output given arbitrary inputs. I will denote this concept *pulse generator and oscilloscope—system identification.*

5.1.3 Network Analyzer

A totally different method involves a *network analyzer* (NWA) [3]. A NWA characterizes the transmission channel in the *frequency domain* [4]. Since most of the specifications on NIF signals are in the *time domain* [6], Fourier transforms [13] must be employed to convert the frequency-

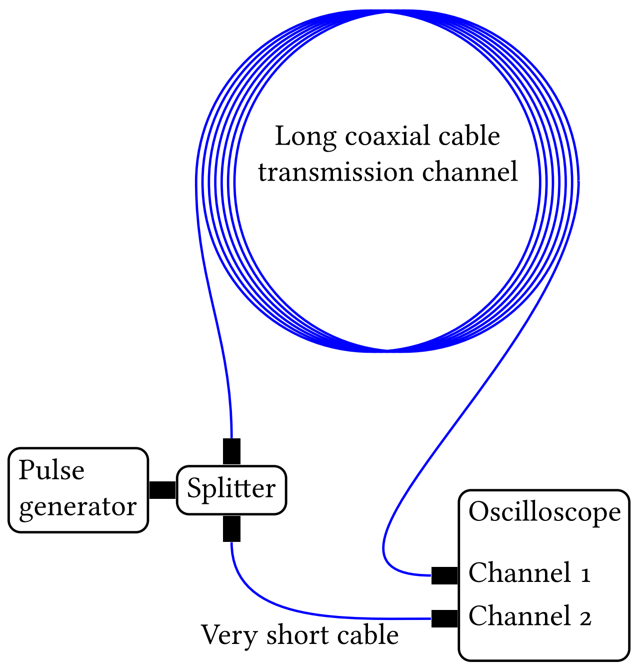


Figure 14: Method using pulse generator and oscilloscope. This figure applies to both the pulse generator/oscilloscope with signal combination and pulse generator/oscilloscope with impulse response approaches

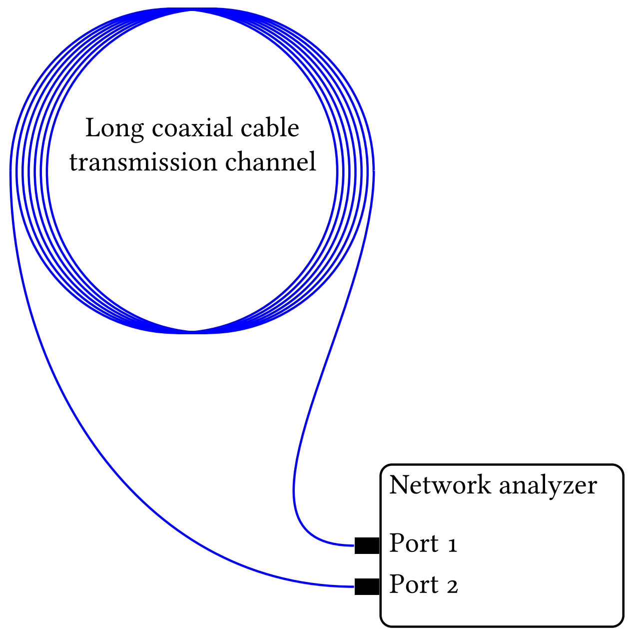


Figure 15: Method using network analyzer. This figure applies to both network analyzer with impulse response and network analyzer with frequency response approaches

domain characterization from the NWA to a time-domain representation. Specifically, an inverse Fourier transform is used to convert the NWA measurements into a time-domain impulse response model of the transmission channel. As before with the pulse generator method, once that impulse response model is computed, it can be used to determine the transmission channel output given arbitrary inputs. I will denote this concept *network analyzer—impulse response*.

A similar approach is to use a Fourier transform to transform a signal of interest into the frequency-domain. The frequency-domain representation of the input signal to be simulated can then be modified by the NWA measurements and then result transformed back into the time-domain via an inverse Fourier transform. I will denote this concept *network analyzer—frequency response*.

5.1.4 Sine wave generator and oscilloscope

A similar approach to the NWA method, at least generally speaking, is the method using a sine wave generator and an oscilloscope. This is a frequency-domain method, like the NWA technique, where sine waves are injected into the transmission channel and the magnitude and phase of the outputs from the transmission channel are recorded. The operator must step through a range

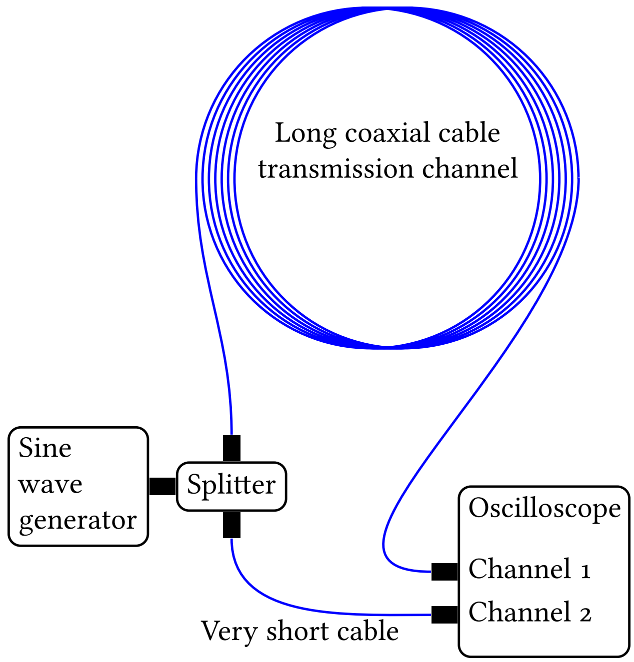


Figure 16: Method using sine wave generator and oscilloscope

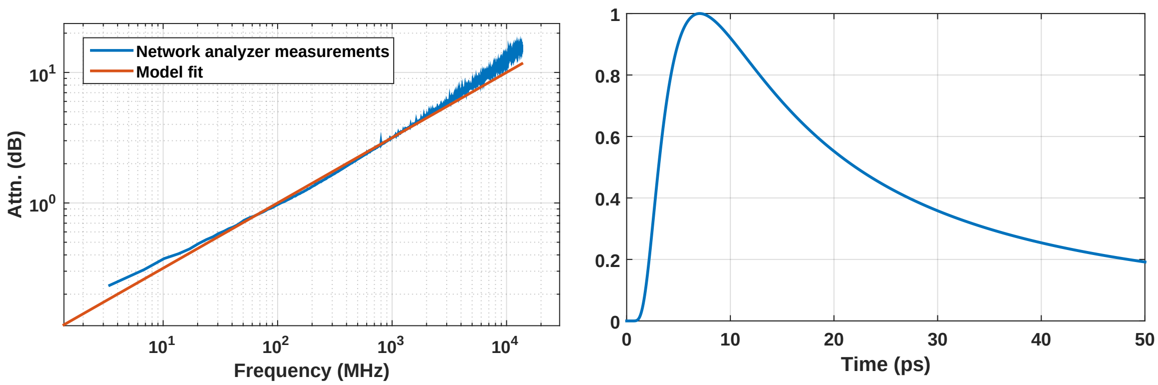
of frequencies and capture the pertinent information in oscilloscope files. The whole process could be automated. Once the frequency-domain characterization of the transmission channel is accomplished, the processing follows along the same lines as with the NWA.

5.1.5 Semi-analytical

In addition to the measurement-intensive methods above, there are *semi-analytical* methods. By semi analytical, I mean that this class of methods uses some measurements, but incorporates them into physics-based models to characterize the transmission channel in the time- or frequency-domain. One example is the method in Ref. [14]. See Fig. 17 for an example of its use.

5.2 Pugh matrix

Table 1 is the Pugh matrix for concept selection. Consider first the weights column in Tab. 1. The weights are from 1 to 10, with 10 being the highest and 1 the lowest. Note that there are ten items that I have ranked. The first seven in the table are the sacred expectations, and the last three are a condensed version of the expectations. The constraints have the highest weights, starting with the ultimate constraint not to impact the shot schedule at all. Next in priority are funding and



(a) Measured coaxial transmission channel attenuation and model fit

(b) Normalized impulse response simulated using model fit

Figure 17: Simulation of impulse response of a very long section of LMR-600 based on network analyzer attenutation measurements.

NIF policies and procedures, respectively. The sacred expectations are weighted according to the rough priority order in Sec. 1.3.

Table 1 also provides a rating of each of the 10 concepts against the sacred expectations and constraints. The ratings are 1 to 5, with 5 being the highest and 1 the lowest. Note that only the ratings relative to the sacred expectations and the funding constraint are meaningful for concept selection, since all of the options rate equally well for the other two constraints.

The *Total* row in Tab. **??** is the sum of the ratings multiplied by the weights for each concept column, which I will call the *weighted score*. Note that there is not much of a difference in the weighted scores. However, the order of the weighted scores does make sense. The pulse generator and oscilloscope with system identification has the highest weighted score because it is accurate and has average performance in the other categories. The AWG with oscilloscope is a close second because it is very accurate and performs well in the other categories, except for those dealing with cost. The NWA methods are next, suffering from some cost and simplicity issues. Accuracy is the driver for the lower weighted scores of the signal combination pulse generator and oscilloscope concept and the semi-analytical approach. In view of the small differences among the weighted scores, I would recommend starting with the highest-ranking method, but also including other methods as resources allow.

The Concepts in Order of Weighted Score

1. **Pulse generator and oscilloscope—system identification**
2. Arbitrary waveform generator and oscilloscope
3. Network analyzer—impulse response
4. Network analyzer—frequency response
5. Pulse generator and oscilloscope—signal combination
6. Semi analytical

The concept with the highest weighted score is the selected concept and is listed below:

The Selected System Concept

Pulse generator and oscilloscope—system identification

	Weights	AWG and scope	Pulse gen. and scope—sig. comb.	Pulse gen. and scope—sys. ident.	NWA—impulse resp.	NWA—freq. resp.	Semi analytical
Accurate	7	5	3	4	5	5	2
Reliable	6	4	3	3	5	5	5
Available to users for their own independent use	5	1	3	3	1	1	1
Simple to implement	4	4	2	2	2	2	3
Simple to use	3	5	5	5	3	3	4
Reasonably fast	2	5	4	4	3	3	4
Ability to provide accuracy information	1	5	2	2	4	4	1
Funding	9	1	3	3	2	2	3
NIF policies and procedures	8	5	5	5	5	5	5
Does not impact shot schedule at all	10	5	5	5	5	5	5
Total		209	204	211	205	205	199

Table 1: Pugh matrix for concept selection. Note that the highest-ranking concept is the pulse generator/oscilloscope with impulse response approach. However, the concept rankings differ by very little. Thus, I would recommend starting with the highest-ranking method, but also including other methods as resources allow.

6 Proposed System Operational Architecture

Figure 18 depicts the proposed system's operational architecture. The interactions with the system are quite similar to those in the existing system (Fig. 10). However the internal workings of the system are different, particularly the presence of a channel simulation capability.

6.1 An Illustration of a Use Case

In order to illustrate the utility of the proposed system, I include a use case drama below. It is ficticious, although it is based somewhat on actual needs, events, and measurements. Further, the measurements are real (taken and time-aligned by J. G. Cruz (Ref. [15]) for an entirely different purpose than this report). Note that my channel characterization and simulation code that I used to process the measurements is still in early stages development, so the results should not be taken as accurate, only the actual measurements. Further, I have arbitrarily shifted and truncated the results for display purposes. I include the results plot to show the sort of information that the system could output.

> A Diagnostic RS asks a Diagnostic RSE, "What will 100 ft. of LMR-600 do to the signal from my sensor?" They decide to employ NIF trusted coaxial transmission channel characterization and simulation methods that use the pulse generator/oscilloscope with impulse repsonse approach. Accordingly, they consult a NIF worker who agrees to make the measurements for them.
>
> The NIF worker locates an appropriate pulse generator, oscilloscope, 100 ft. of LMR-600, a splitter, and connectors and auxiliary cables for the setup in Fig. 14. He then assembles the hardware and makes the measurements. Fig. 19 shows the Channel 1 and Channel 2 oscilloscope traces.
>
> The Diagnostic RS and RSE copy the data in a convenient format and take it back to their offices. The RS asks the RSE to simulate the output of the 100 ft. of LMR-600 for a 200 ps unit-amplitude gaussian pulse, which happens to be very close to the signal he expects his sensor to output.
>
> Accordingly, the Diagnostic RSE loads the data onto his computer and imports it into the channel characterization code, which yields the impulse response of the 100 ft. of LMR-600. This completes the characterization of the channel. Next, he feeds the data, the impulse response, and the 200 ps unit-amplitude gaussian pulse into the channel simulation code, yielding Fig. 20. The code also outputs confidence intervals for the result. He writes a quick report and emails that and the analysis data in a convenient format to the Diagnostic RS, who loads it into his software of choice.

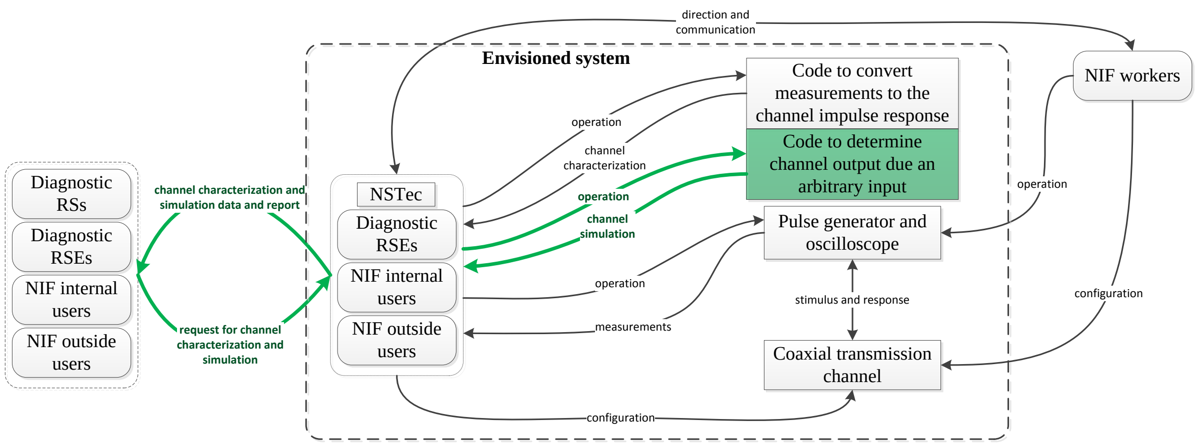


Figure 18: Proposed system operational architecture

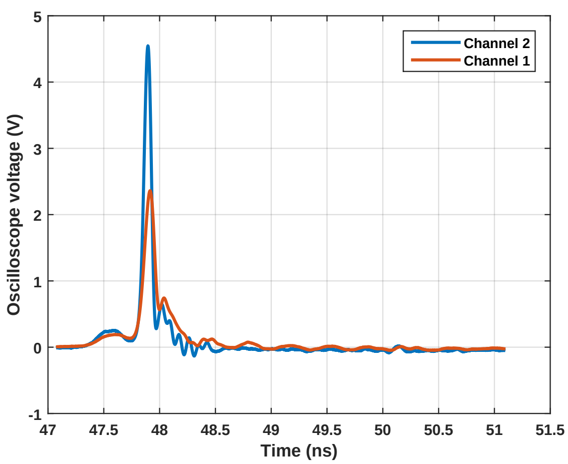


Figure 19: Actual pulse generator/oscilloscope measurements of 100 ft. of LMR-600, taken by J. G. Cruz [15].

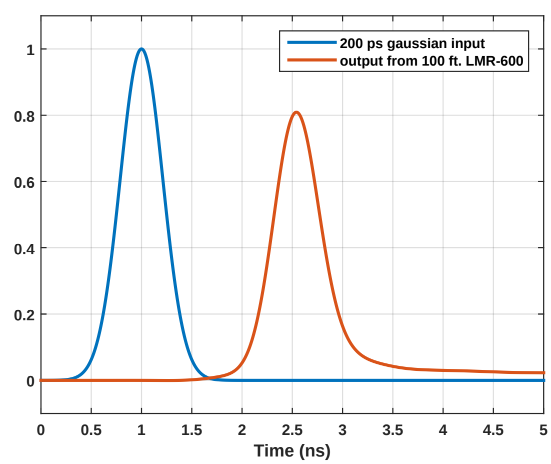


Figure 20: Notional output from proposed channel characterization and simulation system. The results in this figure should not be taken as accurate. Only the actual measurements in Fig. 19 are accurate.

> The Diagnostic RS examines the results and notices a slight risetime degradation, slight widening of the pulse, and the appearance of a tail. None of these distortions are out of his diagnostic's specified requirements, so he concludes that 100 ft. of LMR-600 is an acceptable transmission channel for the signals of interest in his diagnostic. He includes figures from the Diagnostic RSE's report, as well as some of his own, in design review slides for his upcoming conceptual design review. Later, at the conceptual design review, no one has a problem with the length of the transmission channel because of the strength of his analysis.

7 System Requirements

I this section I examine the system requirements, first by employing a small portion of the *Quality Function Deployment* (QFD) [16] framework to correlate the characteristic (non-functional) sacred expectations with certain more tangible aspects of the system.

7.1 Quality Function Deployment Matrix

Table 2 shows the QFD matrix, where I have used the weights from Tab. 1. Note that the capability (functional) sacred expectation is not listed in the QFD matrix. I address requirements related to it later in this section. The correlation values that I used in Tab. 2 are as follows: 9 for high correlation, 3 for medium correlation, 1 for low correlation, and 0 for no correlation. The totals are weighted column-wise sums, similar to those in Tab. 1.

7.2 List of System Requirements

In order to assemble a list of system requirements based on the sacred expectations, I started with the QFD matrix (Tab. 2) column with the highest weighted score: *Quality of code* and itemized requirements based on that aspect of the system. I followed the same procedure for all of the columns of the QFD matrix in descending order of weighted score. I also kept in mind the capability sacred expectation, *Ability to provide accuracy information*, and inserted requirements for that expectation where appropriate. The result of that procedure is in Tab. 3, where I have listed all of the derived requirements, along with the sacred expectations with which they are correlated.

	Weights	Calibration quality	Signal to noise ratio	Connector quality	Cable quality	ESD sensitivity	Quality of test data	Quality of algorithm	Quality of code
Accurate	7	9	9	9	9	0	3	9	9
Reliable	6	9	3	9	9	3	1	3	9
Available to users for their own independent use	5	1	0	1	1	0	3	3	9
Simple to implement	4	9	1	3	3	9	0	9	9
Simple to use	3	9	1	3	3	9	1	9	9
Reasonably fast	2	9	1	1	1	3	1	9	9
Total		203	90	145	145	87	47	177	243

Table 2: QFD matrix for the characteristic sacred expectations of the proposed system

System requirements	Correlated sacred expectation(s)
The code shall use a high-quality, modern language	1,2,3,4,5,6
The code shall have test data and have test capability	1,2,3,4,5,6
The code and test data shall be reviewed by the code author and another individual	1,2,3,4,5,6
The calibration method shall allow for and output error estimation	1,2,4,5,6,7
The version control and repository system shall have triple redundancy	2,3,4,5,6
The algorithm and code shall allow for and implement error estimation	1,2,4,5,6,7
The algorithm shall be reviewed by the author and another individual	1,4,5,6
The connectors and cables shall be instrument grade or better, or according to manufacturer specification	1,2
The combined signal to noise ratio of the entire system, oscilloscopes and code output, shall be quantified and distributed	1,3,7
Manufacturer-specified ESD precautions shall be taken when using the oscilloscopes	2,4,5
Manufacturer-specified oscilloscope, connector, and cable use and care instructions shall be followed	1,2,4,5,6,7

Sacred expectations numbers

1. Accurate (characteristic)
2. Reliable (characteristic)
3. Available to users for their own independent use (characteristic)
4. Simple to implement (characteristic)
5. Simple to use (characteristic)
6. Reasonably fast (characteristic)
7. Ability to provide accuracy information (capability)

Table 3: Requirements for the proposed system. Below the requirements list is a list of the sacred expectations from Sec. 1.3 for reference for the numbers used in the *Correlated sacred expectations* column.

8 Organizational and Business Impact

A coaxial transmission channel characterization and simulation system, as described in this report, could increase the reliability of and confidence in some experiments at NIF, generally for those currently outside of the official NIF data processing system.

The capability boost will impact mostly outside users and internal NIF users, particularly with new and/or temporary coaxial transmission channels that are a part of experiments that occur infrequently. This includes a large portion of national security experiments and some internal NIF proof-of-concept and prototyping tests. Even users of the permanent NIF coaxial transmission channels, which have been characterized, could benefit from improved characterization and simulation for the aforementioned stakeholders.

Further, the proposed system could improve diagnostic design, as well as reviews for diagnostics. An accepted channel characterization and simulation method would assist diagnostic design and design reviews, particularly in the conceptual stage, through meaningful specifications and virtual testing during design.

Work on a coaxial transmission channel characterization and simulation system could be an important step toward extending channel equalization to those currently outside of the official NIF data processing system.

For a more detailed perspective on the organizational and business impact of the coaxial transmission channel characterization and simulation system proposed in this report, refer to Sec. 1, particularly Sec. 1.2.

9 Risks and Technology Readiness Assessment

First, I will address risks, both safety (personnel and facility) in the following section. I the next section I will examine project risks (chance of succeeding) by looking at technology readiness.

9.1 Risks

As indicated in Tab. 1, all of the proposed concepts, including the selected one, have negligible safety risks, both from a personnel and facility perspective. None of them increase the safety risk beyond the current level.

9.2 Technology Assessment

The main technological items needed for this project to succeed are physical equipment (pulser, oscilloscope, computer, *etc.*) and algorithms and code (channel characterization and simulation).

coaxial transmission channel characterization and simulation system.

The physical equipment currently available on commercial-off-the-shelf market is sufficient for the needs of this project. This includes pulsers and oscilloscopes.

The more theoretical and computer-based aspects are also low-risk. First, there is a solid on-site base of signal processing and coding expertise. With that base and the extensive literature available on system identification, it is easy to rate the technical risk of this proposed system as very low.

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